# Improving Southern California Seismic Hazard Models With a 45-km Shear Velocity Profile Along the San Gabriel River

External Grant Award Number 03HQGR0068

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**NEHRP Element(s):** I **Keywords:** Site effects, Surficial deposits, Seismic zonation, Engineering seismology

**Non-Technical Project Summary**

Traditional methods to test how sturdy the ground is can be costly and traffic noise can interfere. We use sounds from the streets to determine how a quake will affect a city. A truck hits a crack in the street and waves radiate from it. If the waves travel slowly, the soil is soft. If the waves travel fast, the soil is hard, and will not shake as much during an earthquake. Knowing the true foundation of a city will help us create better hazard maps. Recent tests show the ground in some big cities is harder than previously thought.

(Abridged from Heineman, K. [producer], 2003, Shaking things up: news short on the San Gabriel River transect in the *Discoveries and Breakthroughs Inside Science* series by NewsProNet Productions, subscribed to by 43 stations nationally, August, 1 min 41 sec. Mailed to grant program managers on VideoCD.)

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Material from Thelen et al. (2004b) is included here as the technical abstract and body of the final report.

# A Transect of 200 Shallow Shear Velocity Profiles Across the Los Angeles Basin

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## Abstract

This study assesses a 60 km NNE-SSW transect for shallow shear velocities along the San Gabriel River, in the San Gabriel Valley and Los Angeles Basin of southern California. The maximum transect 30-meter shear velocity ($V_s^{30}$), occurring in the Valley where the San Gabriel River exits the San Gabriel Mts., is 730 m/s, upper NEHRP hazard class C. Much of the NE section of the transect (in San Gabriel Valley) is also NEHRP class C, or on the C/D boundary. The section of the line south from Whittier Narrows to Seal Beach is NEHRP-D. The lowest velocity, 230 m/s at Alamitos Bay, is NEHRP-D despite predictions of lower velocities on site-classification maps. A rise to the NEHRP C/D boundary occurs at the shoreline outside Alamitos Bay, confirmed by cross lines at Seal Beach, Long Beach and Terminal Island. Measured $V_s^{30}$ values generally show good correlation with published site-classification maps. However, there is no evidence in the data for the NEHRP-B or NEHRP-E hazard classes predicted by these maps. Quaternary geologic units and USDA soil units do not correlate with shallow shear velocities sufficiently for $V_s^{30}$ prediction at any given site. The $V_s^{30}$ data show a fractal spatial dependence, which may break down over distances less than 700 m. Large measurement populations are necessary to properly characterize $V_s^{30}$ trends within a geological surficial unit. The San Gabriel River's hydraulic gradient and local grain size may prove better predictors of $V_s^{30}$ and its spatial variability.


## Introduction

We evaluate a 60-km transect for shallow shear velocities along the San Gabriel River, southern California (Fig. 1). The experiment, completed in July 2003, is designed to evaluate the spatial variability of earthquake shaking hazard, as determined by National Earthquake Hazards Reduction Program (NEHRP) classification, and any velocity correlations to mapped geological and soil units. This study was inspired by the transect of Scott et al. (2003 submitted) across the Reno, Nevada area urban basin, in which 55 shear-velocity profiles were collected utilizing the same methods as this study. They found that 82% of their measurements were significantly higher than predicted from geologic maps by regional hazard assessments (e.g., Wills et al., 2000).

*Background* – Shallow shear wave velocities ($V_s^{30}$) have proved to be important indicators of horizontal acceleration and surface wave amplification produced in geologic units by strong ground motions related to earthquakes (Tinsley and Fumal, 1985;

Borcherdt et al., 1991; BSSC, 1998). The vertically averaged 30-meter shear velocity ($V_s^{30}$) is used to define a NEHRP soil hazard classification for earthquake shaking as outlined by the NEHRP-UBC provisions (BSSC, 1998). The most common method for obtaining $V_s^{30}$ measurements is through borehole soundings. However, the high cost of borehole measurements has driven the search for alternative methods of estimating $V_s^{30}$ values for NEHRP-UBC code compliance. Louie (2001) developed the *Re*fraction *Mi*crotremor (ReMi) technique as such an alternative. In this method, microtremor noise from sources such as traffic on streets and freeways excites Rayleigh waves, which are recorded by a linear array of vertical refraction geophones. The resulting noise records are transformed into frequency(*f*)-slowness(1/v) space, and a dispersion curve is picked along the slowest velocity of this energy. Forward modeling of the fundamental-mode Rayleigh dispersion curve produces a depth-velocity sounding, which can vertically averaged to the single $V_s^{30}$ value required by the NEHRP-UBC code. Louie (2001) reports the accuracy of $V_s^{30}$measurements, using the refraction microtremor technique, to be ±20%.

Explaining the variations in seismic shaking across the Los Angeles Basin has been an ongoing research topic for nearly 20 years. Tinsley and Fumal (1985) assigned individual shear-wave velocities to each geologic unit in their test area, taking into account age, grain size and depth. In 1994, the Northridge earthquake resulted in unexpected variations of damage and ground motions in and around the Los Angeles area. Immediately thereafter, a number of studies were launched to study ground motion effects in southern California. Park and Elrick (1998) extracted $V_s^{30}$ measurements from boreholes to characterize deposits of different ages. Their results also show that $V_s^{30}$ varies with grain size and age, and accordingly they grouped the geologic units in southern California into eight categories. As part of the Southern California Earthquake Center (SCEC) Phase III Report, Wills et al. (2000) published a site-conditions map for all of California based on localized field mapping, 1:250,000 scale geologic maps and 556 $V_s^{30}$ measurements statewide (Fig. 1). Wills et al. usedseven categories, based on NEHRP classes, to group each geologic unit.

**Methods**

The route for our transect was chosen based on ease of access, ample "microtremor" noise and continuity of the route (Figure 1). Along the 60 km transect, rolled arrays of IRIS/PASSCAL "Texan" single-channel recorders were deployed, each mated to a single 4.5-Hz geophone. Our configuration optimizes the recording of Rayleigh waves at about 3 Hz (Satoh et al., 2001).

Linear arrays of 30 channels at a spacing of 20 m (580 m total array length) were installed for 30 minutes recording time. The vertically oriented geophones were leveled with a bullseye tool to within 10° of horizontal at each channel, and recorded dominantly microtremor noise generated from heavy traffic on Interstate 605 and other nearby surface streets. To assess the continuity of measured shear-velocity values, eight arrays were measured lateral to the transect, as much as 5 km away. Four teams of 3 students enabled each array segment of the transect to be installed in a "chaining" fashion. The total length of the transect with 99 (580 m) array placements was completed in 4.5 days.

For the analysis, each individual array was divided into two 300-m segments (15 channels). Data reduction was performed with Optim's SeisOpt® ReMi™ package, developed by Louie (2001). This analysis produces a velocity-spectral image from each

300-m array that we picked for a Rayleigh-wave fundamental-mode phase-velocity dispersion curve. Each curve is forward modeled to obtain a shear-velocity versus depth sounding. Each sounding was averaged to a 30-m shear velocity ($V_s^{30}$), a standard used in estimating the amplification of ground motions at a given site (Borcherdt et al., 1991; BSSC, 1998).

A potential source of error in the analysis potentially lies in our forward modeling. To minimize modeling bias in the results, three separate analysts were used. Each worker modeled every third sub-array throughout the length of the transect. In this way, any modeling bias of a particular worker would not characterize the results over a particular stretch of transect, especially if a certain section was geologically prone to differences in interpretation. To estimate the error introduced by forward modeling, independent modelers reanalyzed data sets from three randomly selected sites along the line (Table 1). The results show a maximum variance of ±7% relative to the first models.

Throughout the length of the route, shear-velocity values were measured with arrays placed upon a levee between one and four meters in height. To assess the effect of the levee, a shear-velocity measurement on a ~3 m high levee was made and another measurement longitudinally adjacent to the same levee at ground level approximately 30 m away. The results show only a 4.0 m/s difference in $V_s^{30}$ on the levee compared to off the levee, significantly less than the ±20% error in velocity stated generally by Louie (2001). Inspection of the modeled shear-velocity versus depth soundings shows very little difference between the on-levee and the off-levee measurements. One reason for the concordance of the profiles is likely the vertical depth resolution of the method used.

**Results**

The modeled shear–velocity profiles have been projected for the respective intervals onto a vertical cross-sectional plane that extends to 200 m depth below the surface (Fig. 2). The location of interval midpoints on the surface is based on the line distance from the first recording geophone in the mouth of San Gabriel Canyon.

Note that a "dog leg" through the Santa Fe Dam area near Azusa diverts the line in a direction transverse to the San Gabriel River and results in a relatively high density of data points over the corresponding longitudinal interval of river course (Fig. 1). Likewise, the respective $V_s^{30}$ values have been plotted as a function of line distance (Fig. 3). The effects of elevation changes are negligible in these projections.

Near the San Gabriel range front at the mouth of San Gabriel Canyon in Azusa, higher velocity materials (>760 m/s) occur at depths of > 40 m, while $V_s^{30}$ values cluster in the 550-660 m/s range. At approximately 10 km away from the range front, thicker deposits of relatively low velocity materials (<550 m/s; light shades on Fig. 2) are first observed. Our highest measured velocities occur 5-10 km along the transect from the range front in Azusa, not in the San Gabriel Mts., at depths greater than 75 m. Our lowest velocities occur near the surface at approximately 56 km from the mouth of San Gabriel Canyon near Alamitos Bay (Fig. 2).

The modeled $V_s^{30}$ values from each of 199 transect arrays and eight lateral arrays are shown graphically in Figure 3. Between Azusa and the Santa Fe Dam area (0-10 km), $V_s^{30}$ values reveal a NEHRP-C (350-760 m/s) classification. Values in this interval are more spatially heterogeneous than elsewhere in the transect. North of the Whittier Narrows Dam from the Santa Fe Dam area (10-37 km), values fluctuate at the NEHRP C/D boundary. From Whittier Narrows south to the end of the line at Seal Beach, the modeled $V_s^{30}$ values are classified NEHRP-D (150-350 m/s). The spatial variability in the interval between Whittier Narrows and Seal Beach is far less than values north of the Whittier Narrows. A rise in velocities past Alamitos Bay to the NEHRP C/D boundary is supported by corroborating measurements at Seal Beach, Long Beach and Terminal Island (Fig. 3).

To explore the relationship of $V_s^{30}$ to surficial geology and soil type, we compared the distribution of surficial units designated by Quaternary geologic maps (CDMG, 1998) and soil maps (NRCS, 1969) to the distribution of $V_s^{30}$ over the transect. Each midpoint of a 300-m sub-array was associated with a geologic unit and soil type. The measured $V_s^{30}$ values are plotted against geologic unit and soil type in Figures 4 and 5, respectively. Refer to Tables 2 and 3, respectively, for descriptions of each of the units.

**Discussion**

*Velocity section*– Shear-velocity trends in the gridded section (Fig. 2) and as discussed above are consistent with velocities predictable from the geologic context of the major topographic divisions of the line. For example, near the mouth of San Gabriel Canyon, high velocities (≥800 m/s) come to within 40 m of the surface, suggesting thick sequences of well-graded boulders and cobbles below that depth. At ~10 km from the range front, the high velocities show an abrupt deepening, suggesting a change from very coarse fan-type detritus to finer grained alluvial material. Likewise, the thickness of low-velocity material increases with distance from the range front, probably reflecting the increasing fraction of sands and silts as the River's hydraulic gradient decreases.

*Comparison with Wills et al. predictions*– In order to facilitate the discussion of our results, we compare our $V_s^{30}$ results to those of Wills, et al. (2000) in Figure 3. The $V_s^{30}$ measurements in shallow Quaternary alluvium and some Precambrian crystalline basement rocks near the San Gabriel Mountains range front (0-2 km, Figures 2 and 3), lie within the NEHRP-C range and at the low end of the predicted range of Wills, et al. This difference is likely due to the pervasive fracturing and a thick weathered zone that has probably developed within the feldspar-rich gneiss. Local variability in fracture density and the presence of a veneer of coarse alluvium and colluvium probably also contribute to our measured $V_s^{30}$ values being lower than expected for granitic bedrock outcrops.

From Azusa to the Santa Fe Dam area (2-10 km, Figures 2 and 3) the measured $V_s^{30}$ values are higher than those predicted by Wills, et al. This is most likely due to the presence of coarser deposits of boulders and cobbles at shallow depths than is observed in the surficial geology. From the Santa Fe Dam south to near El Monte (15-30 km, Figs. 2 and 3), the modeled velocities are higher than predicted, also possibly due to buried gravelly intervals or lenses as shallow depths. Such inferred coarser intervals may have been widely deposited across this portion of the transect if the course of the San Gabriel River experienced significant channel migration in Quaternary times. Channel migration would be expected across this large alluvial fan. Such deposits might also be expected with the higher volumetric discharge characteristic of past pluvial periods. Hence the elevated $V_s^{30}$ measurements suggest an overly broad characterization of the San Gabriel River flood plain by Wills, et al.

From the Whittier Narrows to the terminus of the line at Seal Beach (30-60 km, Figs. 2 and 3), almost all of the measured $V_s^{30}$ values are in agreement with the site-conditions map of Willis, et al. The agreement here with the classification of Wills, et al.

in this more distal-fluvial portion of the transect is consistent with our interpretation above of the Azusa to El Monte sections.

For a dominant portion of the transect, the $V_s^{30}$ values are near the high-end of the range predicted by Wills, et al. (Fig. 3). It is noteworthy that the measured $V_s^{30}$ for the upper 17 km of the transect fall within a NERHP-C classification (350-760 m/s) rather than within the NERHP-C-D or NERHP-D classifications assigned by Wills, et al. for this interval. It is further significant that none of our measurements could be interpreted to support a NERHP-E classification (<150 m/s; Figure 3) of $V_s^{30}$, as characterized by Wills, et al. for the Alamitos Bay area north of Seal Beach (Figs. 1 and 3).

*Hydraulic gradient*– Interestingly, the shape of the $V_s^{30}$ vs. distance curve (Fig. 3) loosely mimics the modern hydraulic gradient of the San Gabriel River from the river head at 0 km to its embayed terminus at 58 km. This similarity is most likely due to fining grain sizes with decreasing average slope at increased distances from the range front. Furthermore, where the hydraulic gradient is currently high, the relative heterogeneity in measured $V_s^{30}$ is also high. Such high heterogeneity is here interpreted as a product of discontinuous and heterogeneous fanglomerate bodies deposited proximal to the tectonically active range front of the San Gabriel Mountains during Quaternary times. Note that as the modern hydraulic gradient decreases, the spatial heterogeneity of $V_s^{30}$ values decreases (Fig. 3). We interpret these changes to reflect an increased fraction of sand and silt and a greater lateral continuity of deposits in the shallow subsurface, both concomitant with the change to a more distal alluvial and fluvial setting.

*Measurements away from the River channel*– In order to test the continuity of our transect results, corroborating measurements were taken along lines perpendicular to our transect, up to 5 km laterally away from the transect. These locations are translated back upon the line and the measurements plotted together with the transect values on Figure 3. Our lateral $V_s^{30}$ measurements agree very well with our transect values (Fig. 3).

The exception to this trend occurs near the range front where highly variable geologic history characterizes the longitudinal $V_s^{30}$ profile. For example, a few kilometers to the east of the transect in Azusa, $V_s^{30}$ values are approximately 160-180 m/s less than those taken on the transect near the San Gabriel River mouth (Fig. 3). At that location, the $V_s^{30}$ measurements were made in inactive alluvium with a well developed soil, on a terrace elevated above the modern riverbed. We attribute this heterogeneity observed near the range front to abrupt facies changes within the surficial deposits and abrupt lateral changes in deposit ages and burial histories (and hence weathering and lithification). In the case of the Azusa terrace, shear wave velocities suggest a finer grained deposit that was never buried.

*Velocity correlations with map units*– Comparisons of $V_s^{30}$ values measured *within* mapped Quaternary geologic and soil units reveal no obvious relationships. Broad distributions with large ranges of up to ±150 m/s in $V_s^{30}$ values are observed in ten out of the eleven Quaternary geologic units encountered in the transect (Fig. 4). Moreover, small variations in $V_s^{30}$ are observed *between* different units (Fig. 4). It is worthy of note that in designating surficial units, Quaternary mappers may "lump" several sedimentary deposit types. Such characterizations may be based upon surface and morphologic expression in aerial photographs rather than deposit texture, lithification, and thickness. Hence mapped units may be poor predictors of the elastic properties of the units for depths exceeding several meters. In addition, the criteria for unit designations are somewhat subjective and may vary from worker to worker. Wills et al. (2000) recognized this and further lumped units together.

Five of the eight soil types occurring in the transect show very high $V_s^{30}$ variations within the unit (Fig. 5). While we desire to find existing maps that can characterize shear velocities, it is helpful to note that the development of soil is controlled by a number of factors including slope, climate, parent material, biologic activity, and flux of aeolian silt. In addition, the degree of soil development is strongly related to length of deposit exposure at the surface ($10^4$-$10^6$ year scale). In tectonically active areas, some surfaces have convoluted soil-developmental histories caused by alternating periods of active sedimentation and subsequent abandonment. Because soils in the southwestern United States typically extend no more than 2 meters below the ground surface (~7% of a 30 m depth), the degree to which soil development can be considered a strict indicator of the elastic properties of the deposit over a 30 m interval is severely limited. Moreover, soil-forming processes such as biologic activity and aeolian silt influx essentially act at the surface and thus have negligible influence over a 30 m interval.

The three soil types showing a relatively lower variance of $V_s^{30}$ values within the unit are instead indicating the subsections of the hydraulic gradient over which $V_s^{30}$ shows homogeneity regardless of soil type. Note also that slope controls the distribution of clay minerals in the basin, which are key in the designation of mappable soil units. Further, slope also controls texture which in turn affects porosity and ultimately the thickness and type of soil formed. Thus it is only to the extent that soils are predictors of hydraulic gradient that they may be considered rough predictors of $V_s^{30}$.

Because the entire length of the line follows the course of the San Gabriel River, the measurements were predominantly taken on soil types 3 and 4 (Fig. 5), which are formed on fluvial surficial map units. Hence it may be argued that the lack of correlation between our $V_s^{30}$ values and mapped soil and geologic units is an artifact of the transect location. This argument would predict low $V_s^{30}$ values over our transect because shear wave velocity measurements are taken in relatively young and uncompacted fluvial deposits. However, our $V_s^{30}$ measurements throughout the upper two-thirds of the transect are higher than those predicted by Wills, et al. (2000). We infer that the most recent, active alluvium is coarser, better graded, and thus stiffer than less active parts of the sequences.

*Spatial statistics*– To further examine the relationship between the measured $V_s^{30}$ values and the mapped geologic units, the fractal dimension of the spatial curve in Figure 3 was calculated. The fractal dimension was derived from the power spectrum of the $V_s^{30}$ values (Fig. 6). The power spectrum and fractal dimension, when applied to seismic data, can be related to lithologic variation (Mela and Louie, 2000). The power spectrum (Fig. 6) exhibits fractal characteristics. Calculated from the trend line on the log-log plot, a fractal dimension of 1.70 is similar to other spatial measurements of geologic deposits (Mela and Louie, 2000). The confusing relationship between soil units, geologic units and their $V_s^{30}$ values seen in Figures 4 and 5 is therefore real and not an effect of the technique. There is a flattening of the power spectrum near 700 m separation, which is the noise level under which the technique distinguishes lateral $V_s^{30}$variations less accurately.

By analyzing subsampled averages and standard deviations, insights into spatial dependence and variations in velocities can be determined. Here, the largest sampled population of soil unit (4) and geologic unit (7) are extracted to calculate the average and standard deviation of $V_s^{30}$ values for each 25% of the population, 50% of the population and 100% of the population. The partitioning of the data was based on measurement location, i.e., one of the 25% portions was from the southernmost 25% of the transect, another 25% portion was from the northernmost 25% of the transect, etc. Next, the $V_s^{30}$ data were randomized in location and plotted against the spatially sorted data (Figs. 7 and 8). In all cases, the maximum variability occurs at 25% of the population, suggesting a high degree of spatial dependence of the final shear-velocity values.

In unit geologic unit 7 and soil unit 4, the randomly sorted data show much the same behavior as the spatially sorted data, with less variation. In our two highest populations, the soil variability between sections partitioned from different locations along the transect is much higher than the geologic or soil variability\. In both cases, our 100% completeness average reveals an entirely different NEHRP classification than our lowest-velocity 25% and 50% completeness averages (Fig. 7).

The subsampled standard deviation of the analyzed soil unit increases at all completeness values (Fig. 8), due to the inadequacy of soil type as a $V_s^{30}$ indicator. This is intuitively opposite to the behavior of geologically related data, where standard deviations would go down with increasing populations. The randomly sorted data shows behavior that is much more indicative of geologically related data. For the geological unit analyzed, the standard deviations increase with increasing completeness in 3 out of 4 cases. The randomly sorted data shows the same behavior as the spatially sorted data. Further investigations are needed to explore the cause of these behaviors. The magnitudes of the increases in standard deviation is much higher in the soil unit than in the geologic unit, suggesting that the geologic unit may be a better indicator of $V_s^{30}$.

*Borehole comparison*– The Rosrine Project web site (geoinfo.usc.edu/rosrine) describes one logged borehole less than several kilometers from our transect. Figure 9 shows Pico Rivera #2 suspension-logger shear-velocity results plotted against three of our shear-velocity profiles that should be among the closest to this borehole. The borehole is probably less than 500 meters from our transect. (Rosrine gives latitude and longitude for this borehole to three decimal places, and the suspension-logger results, but no lithologic logs, location, or other information.)

Figure 9 shows that our transect ReMi profiles match the Rosrine log very well below 8 m depth. Array number 157A at a transect distance of 33.6 km (Figs. 2 & 3) provides the best match. The modeled velocity increase from 220 m/s to 510 m/s at 14 m depth mimics well a similar sharp increase in the suspension log.

Above 8 m depth, the Rosrine borehole encountered very slow materials, probably unsaturated clays. (The borehole's P-velocity log suggests an 8-m depth for the water table.) The transect arrays were all on the engineered levee, closer to the coarser materials in the active river channel, and where such soft materials may have been removed or modified during levee construction. While array 157A yielded a $V_s^{30}$ of 327 m/s (tested in Table 1), the very soft 100-200 m/s materials logged above 8 m give the Rosrine result a $V_s^{30}$ of only 242 m/s. The 26% error in $V_s^{30}$ is acceptable considering that the measurements are not coincident. Figure 3 does show that one ReMi array 1.5 km to the south of the Rosrine borehole, at 35 km transect distance, yielded a $V_s^{30}$ below 300 m/s.

## Conclusions

This study has measured shear-velocity values at more than 200 individual sites along a 60 km transect from San Gabriel Canyon south to Seal Beach. All 99 transect arrays and eight cross-lines took only 4.5 days to complete. The modeled velocities have depth constraints to no less than 100 m and often many times deeper. The shear-velocity values suggest a general fining of basin deposits with distance from the range front. This is corroborated by an observed thickening of relatively slow-velocity material, presumably sand and silt deposits in contrast with stiffer, well-graded cobble and boulder deposits.

In this study, the derived $V_s^{30}$ agree with published site conditions maps on a broad scale. Individual site analyses shows high degrees of variability for separations greater than 700 m. No evidence for NEHRP-B or NEHRP-E classifications as predicted by Wills et al. (2000) was found along the transect, despite arrays being located on San Gabriel Mts. bedrock and at Alamitos Bay. Published site-classification maps are overly cautious in areas of Quaternary geology and may encourage overly conservative building design.

The hydraulic gradient may play an important role in explaining trends in our $V_s^{30}$ measurements, as well as the relative heterogeneity of measurements from one area to another. Near the San Gabriel River, mapped soil and Quaternary geologic units poorly predict the measured $V_s^{30}$. In a comparison of soil units against geologic units, geologic units are a more accurate predictor of shear velocity values, although the actual degree of correlation between geologic units, soil units and $V_s^{30}$ values is unclear. The data show high degrees of spatial correlation, implying the need for many measurements in each unit in order to derive an accurate average shear-velocity. The evidence points to grain size and slope angle as the dominant factors affecting $V_s^{30}$ measurement values.

Our tentative correlation of $V_s^{30}$ heterogeneity with hydraulic gradient has a large potential impact for individual site analysis. In areas where the modern local slope is low and the sand and silt fraction are high, nearby $V_s^{30}$ measurements may characterize a particular site of interest with acceptable accuracy. Areas with relatively steeper gradients appear to be underlain by localized cobble-texured deposits and exhibit high spatial variability over a 0.7 km scale. Hence in these areas, an individual site analysis should be performed.

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All data and results from this work is available from the web site www.seismo.unr.edu/hazsurv .

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| Distance | Nearest City | $V_{30}$ Values (Orig, remodeled) | $V_{30}$ Average | Standard Deviation ($\sigma$) | ($\sigma/V_{30}$ av.)*100% | Approx. Difference ± % |
|---|---|---|---|---|---|---|
| 0.6 | Azusa | 584.0, 565.0 | 574.5 | 13.44 | 2.34% | 1.17% |
| 33.6 | Whittier | 347.0, 327.0 | 337.0 | 14.14 | 4.20% | 2.10% |
| 58.2 | Seal Beach | 307.0, 251.0 | 279.0 | 39.60 | 14.19% | 7.10% |

**Table 1**

| Symbol | Description |
|---|---|
| Qfb | Active alluvial fan deposits, boulder gravel |
| af | Artificial fills, sand to silty sand, soft to dense, high liquefaction susceptibility |
| Qwg | Active alluvial fan deposits, active wash, gravel |
| Qwa | Active alluvial fan deposits, active wash |
| Qya4a | Young (Holocene?) alluvial valley deposits, arenaceous sand, characteristic grain size: 4a |
| Qyf3a | Young (Holocene?) alluvial valley deposits, arenaceous sand, characteristic grain size: 3a |
| Qya4g | Young (Holocene?) alluvial valley deposits, gravel, characteristic grain size: 3a |
| Qyfa | Younger alluvium, soft sand, loose to moderately dense sand, high liquefaction susceptibility |
| Qyfs | Younger alluvium, silt, loose to moderately dense, high liquefaction susceptibility |
| Qoaa | Old (Pleistocene?) alluvial valley deposits, silty sand, minor gravel, dense to very dense, low liquefaction suseptibility |

Source: CDMG, 1998

**Table 2**

| Soil Number | Description |
|---|---|
| 1 | **Oceano** association, over 60 inches deep, 2 to 5 percent slopes, sands, excessively drained |
| 2 | **Marina-Garey** association, over 60 inches deep, 2 to 15 percent slopes, loamy sand to sandy loam, well to excessively drained |
| 3 | **Tujunga-Soboba** association, over 60 inches deep, 0 to 5 percent slopes, sand or loamy fine sand with up to 35% gravel and cobbles, excessively drained |
| 4 | **Hanford** association, over 60 inches deep, 2 to 5 percent slopes, coarse sandy loam to gravelly loamy coarse sand with courser lenses below 40 inches, well drained |
| 5 | **Chino** association, over 60 inches deep, nearly flat slopes, loam to silt loam to clay loam to silty clay loam, poorly drained |
| 6 | **Ramona-Placentia** association, over 60 inches deep, 9 to 15 percent slopes, loam to sandy loam to clay loam, excessively drained |
| 7 | **Vista-Amargosa** association, 14 to 38 inches deep, 30 to 50 percent slopes, sandy loam, well to excessively drained |
| 8 | **Rock land- Rough broken land** association, very shallow, very flat, rock outcrops, excessively drained |

Source: NRCS, 2002

**Table 3**

Table 1: Velocity-profile modeling error analysis of three random sites along the length of our transect. The first velocity of the second column ($V_s^{30}$ Values) is the original velocity, the second velocity is the reanalyzed value.

Table 2: Key for Quaternary Map units numbered in Figure 4.

Table 3: Key for soil map units numbered in Figure 5.

Figure 1: Location map of the study area. The double line trending North-South is the location of our shallow shear-velocity transect. The site conditions map published by Wills et al. (2000) is shown in the background. Letter labels are NEHRP classifications.

Figure 2: Gridded shear velocities for the entire transect in section to 200 m depth. Zero kilometers is in the mouth of San Gabriel Canyon, and 60 km is at Seal Beach (Fig. 1). Velocity values related to NEHRP classification boundaries are provided.

Figure 3: $V_s^{30}$ values for 200 transect array measurements are shown with dark circles outlined with white. Corroborating measurements are also shown with various symbols projected back upon the transect line. All values are normalized by the distance of the midpoint of the array from the mouth of the San Gabriel Canyon. For comparison, NEHRP classifications from the study by Wills et al. (2000) are shown in light gray.

Figure 4: Measured $V_s^{30}$ values compared to their respective geologic unit (CDMG, 1998). Dark diamonds represent the mean values and bars represent the standard deviation of the measurements. The x-axis is an approximate timescale with the oldest units to the left and the youngest units to the right. Average velocity and standard deviation values are shown below each data point. A key of geologic units can be found in Table 2, by number.

Figure 5: Measured $V_s^{30}$ values compared to their respective soil unit (NRCS, 1969). Black diamonds represent the mean values and bars represent the standard deviation of the measurements. Average velocity and standard deviation values are shown below each data point. Consult Table 3 for a description of soil units, by number.

Figure 6: Spatial power spectra of the modeled $V_s^{30}$ values as a log-log plot. The power spectrum is the gray line and the trend line used to calculate the fractal dimension is shown in black.

Figure 7: Results of average subsampling of $V_s^{30}$ values of soil unit 4 and geologic unit 7. Spatially sorted data are depicted by solid lines and randomly sorted data are shown with broken lines. The NEHRP C/D boundary is also shown.

Figure 8: Results of standard-deviation subsampling of $V_s^{30}$ values of soil unit 4 and geologic unit 7. Spatially sorted data are depicted by solid lines and randomly sorted data are shown with broken lines.

Figure 9: Comparison of Rosrine/USGS Pico Rivera #2 suspension-logger results from geoinfo.usc.edu/rosrine against three nearby ReMi arrays along our July 2003 transect. Below 8 m depth, velocities and interface depths match well. The ReMi arrays were all in the gravel riverbed, and show minimum shallow velocities above 200 m/s. The Rosrine hole is probably <0.5 km away from our transect, but has slow clay deposits in the upper 8 m.

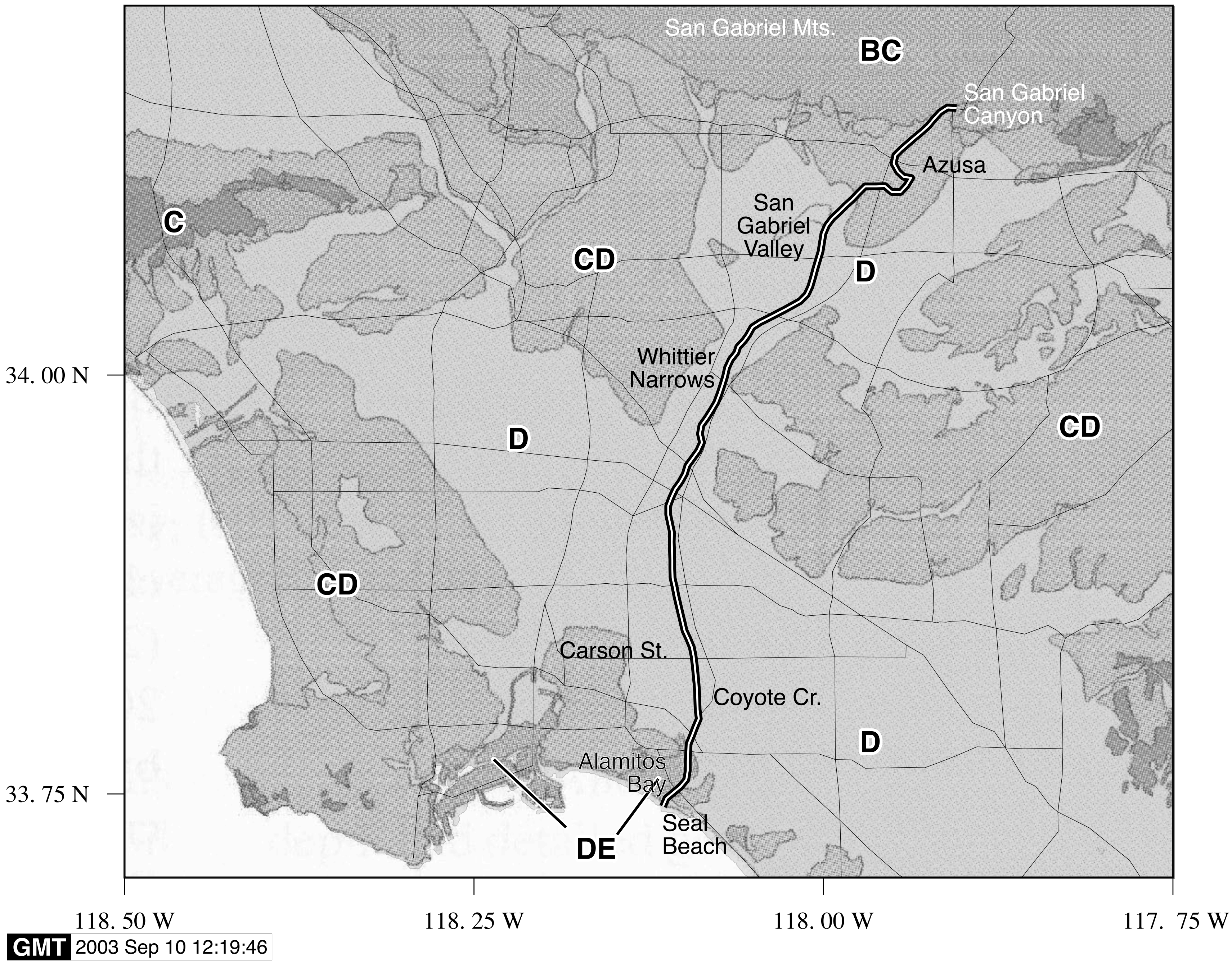

San Gabriel Mts.
BC
San Gabriel
Canyon
Azusa
C
San
Gabriel
Valley
CD
D
Whittier
Narrows
34. 00 N
D
CD
CD
Carson St.
Coyote Cr.
D
Alamitos
Bay
33. 75 N
Seal
Beach
DE
118. 50 W
118. 25 W
118. 00 W
117. 75 W
GMT 2003 Sep 10 12:19:46

Figure 1

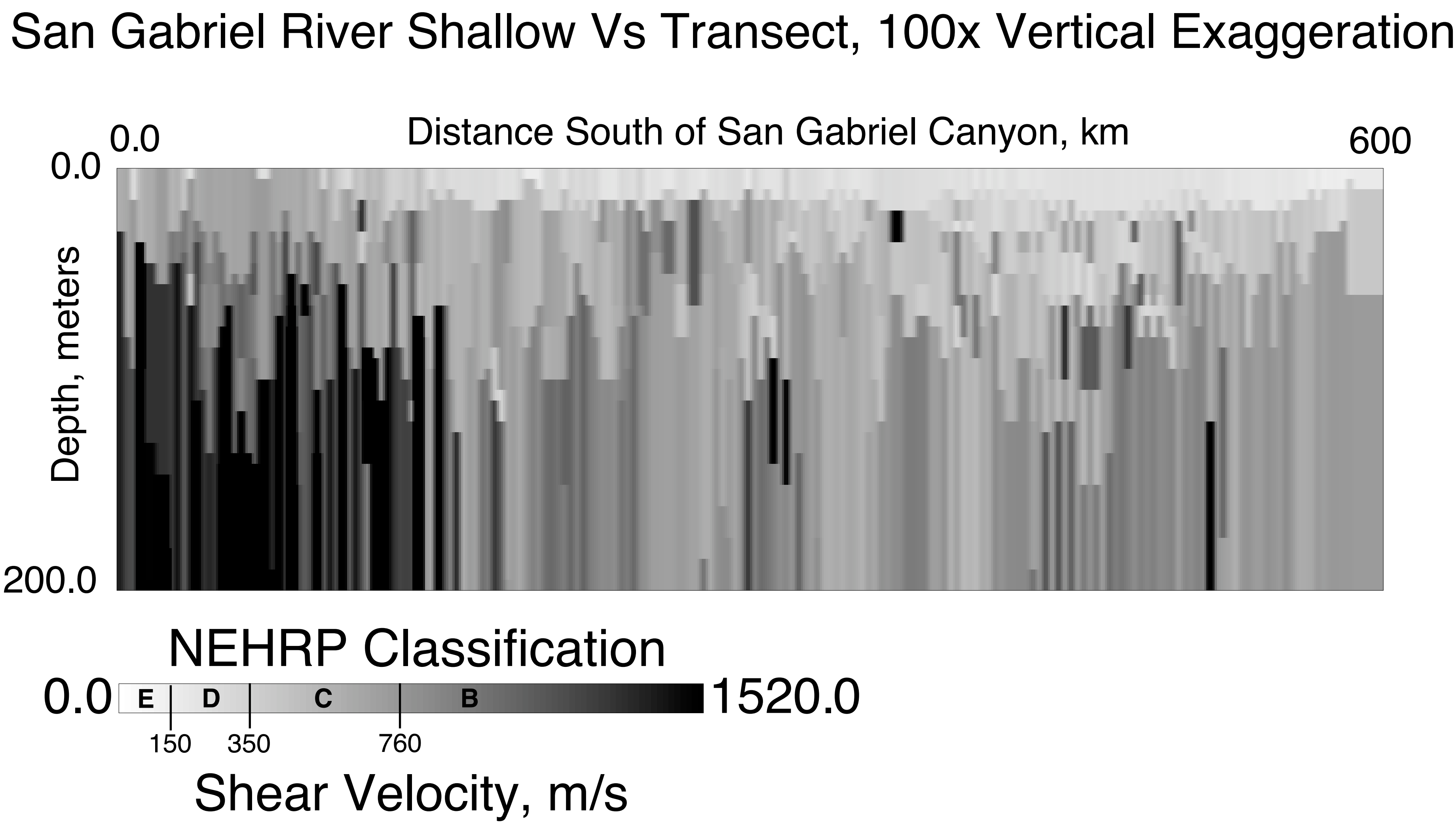
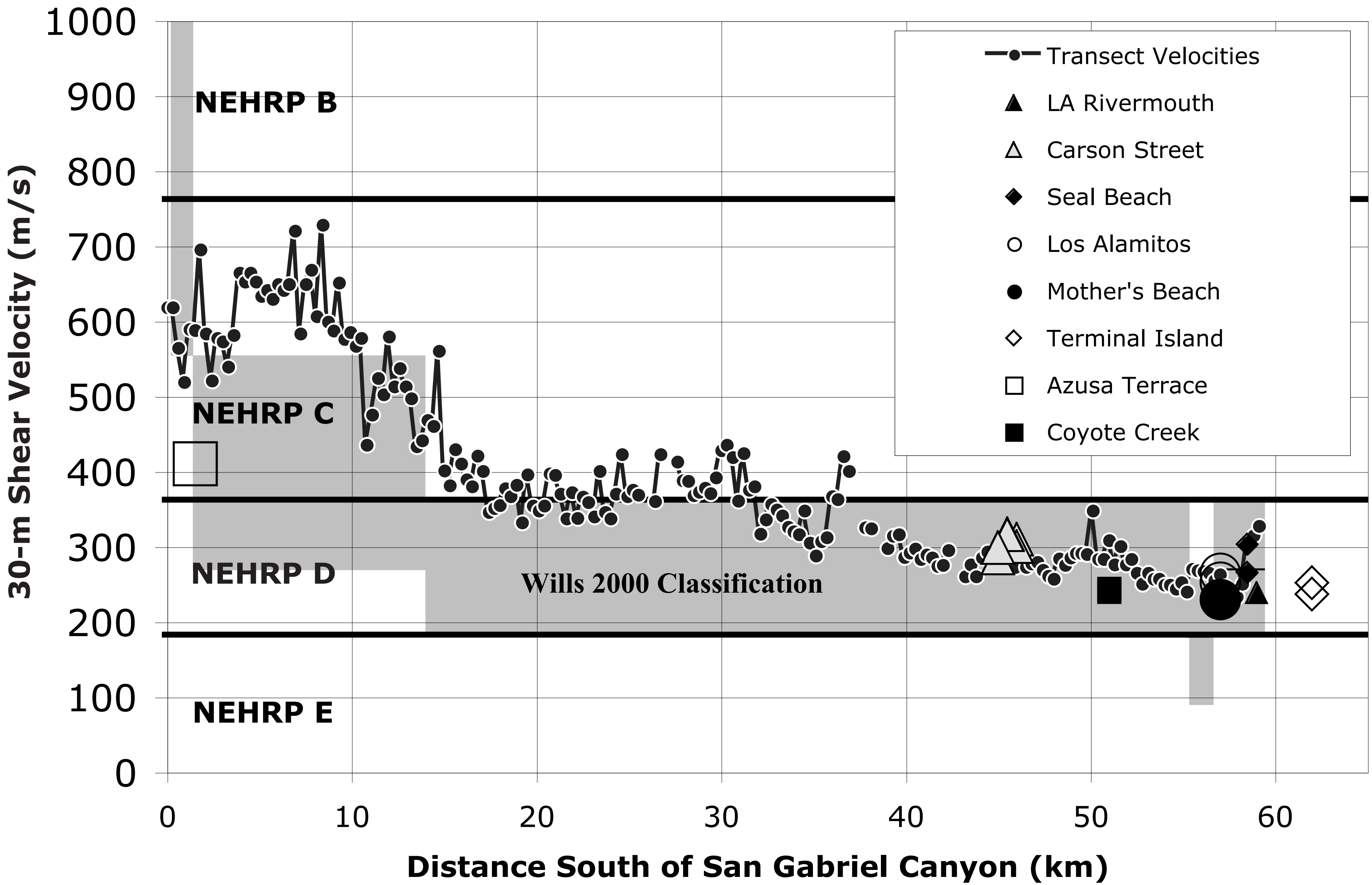

San Gabriel River Shallow Vs Transect, 100x Vertical Exaggeration
Distance South of San Gabriel Canyon, km
0.0
600
Depth, meters
0.0
200.0
NEHRP Classification
0.0
E
D
C
B
1520.0
150
350
760
Shear Velocity, m/s

**Figure 2**



1000
900
800
700
600
500
400
300
200
100
0
30-m Shear Velocity (m/s)
NEHRP B
NEHRP C
NEHRP D
NEHRP E
Wills 2000 Classification
Transect Velocities
LA Rivermouth
Carson Street
Seal Beach
Los Alamitos
Mother's Beach
Terminal Island
Azusa Terrace
Coyote Creek
0
10
20
30
40
50
60
Distance South of San Gabriel Canyon (km)


Figure 3

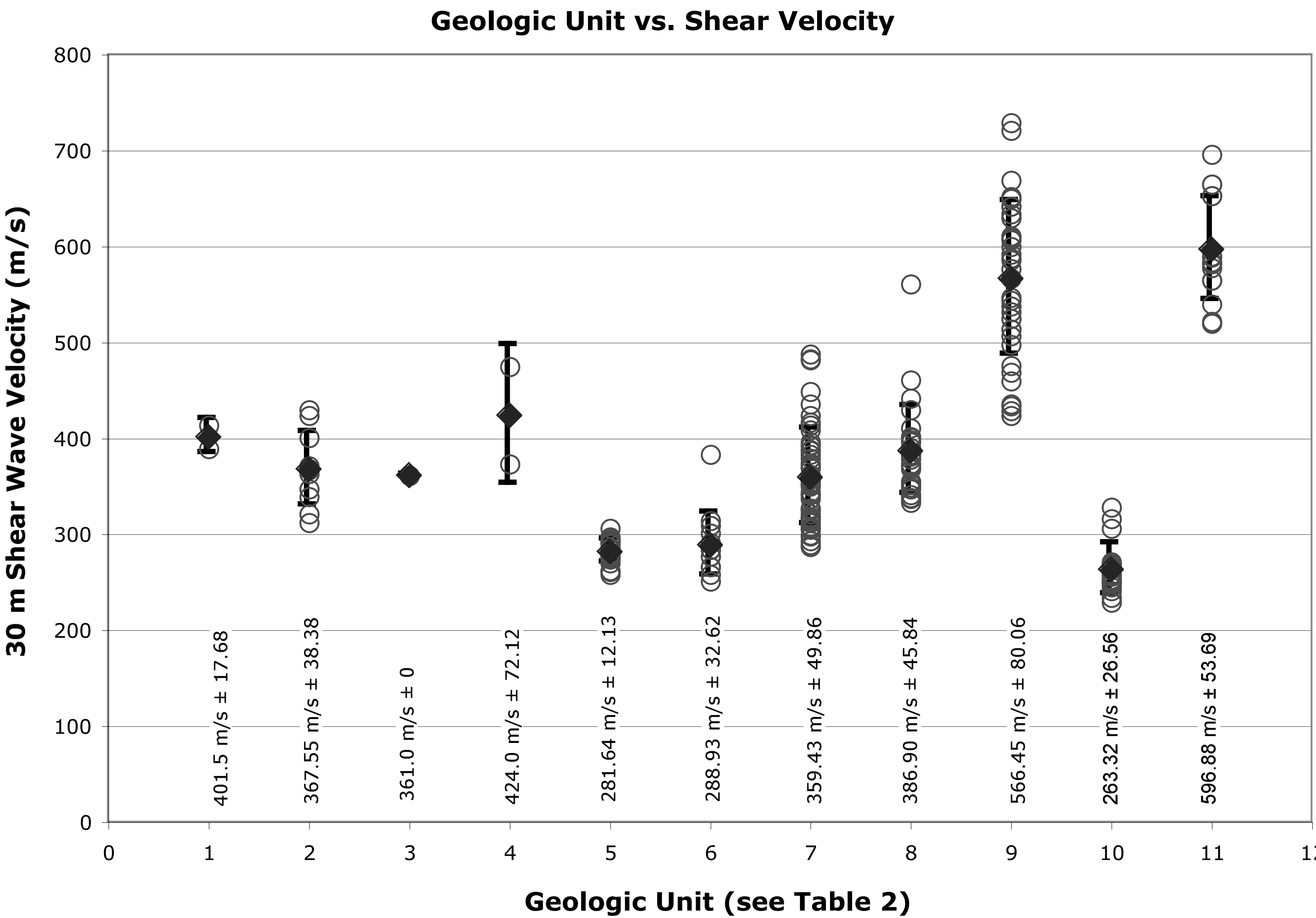
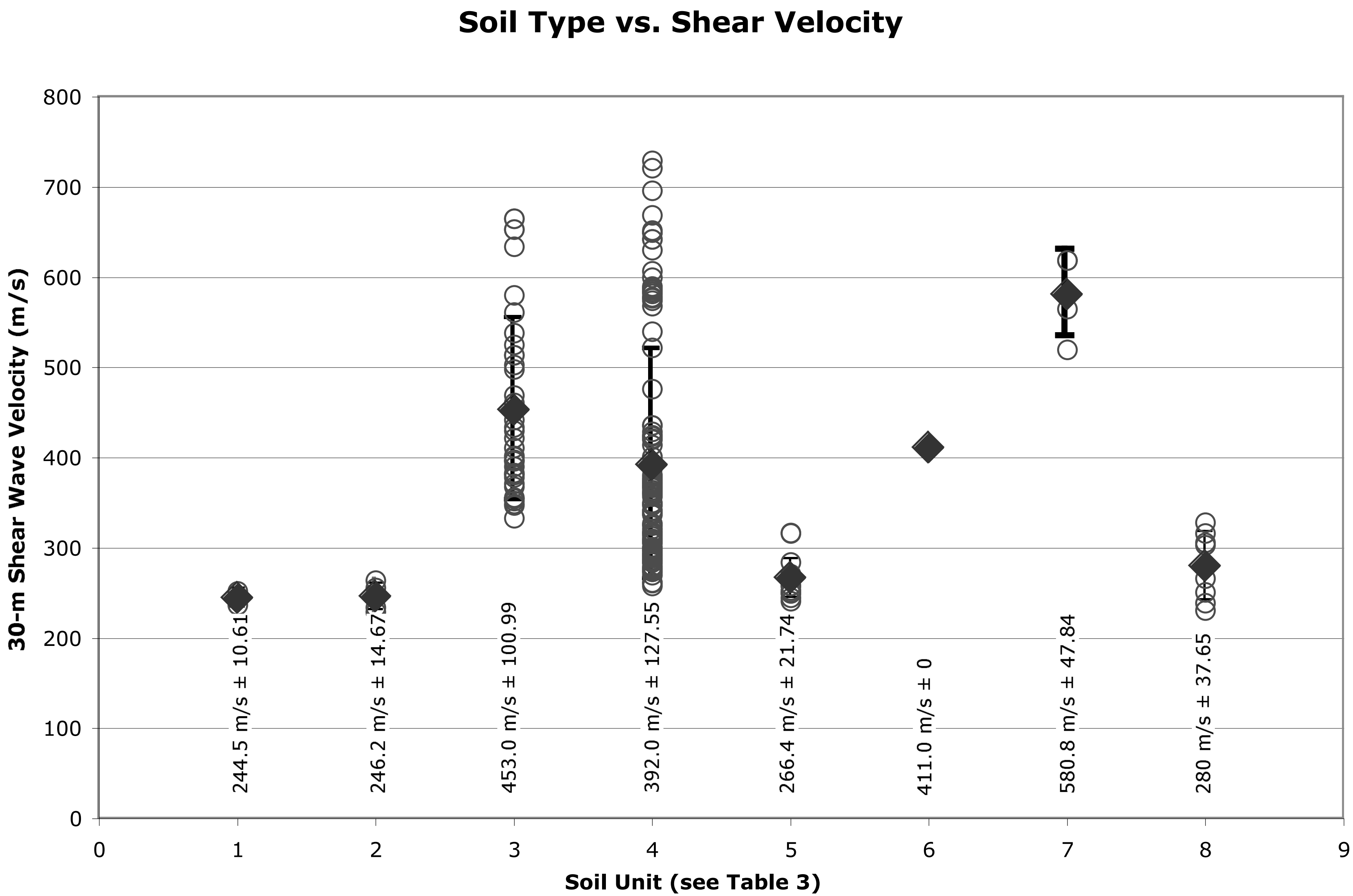
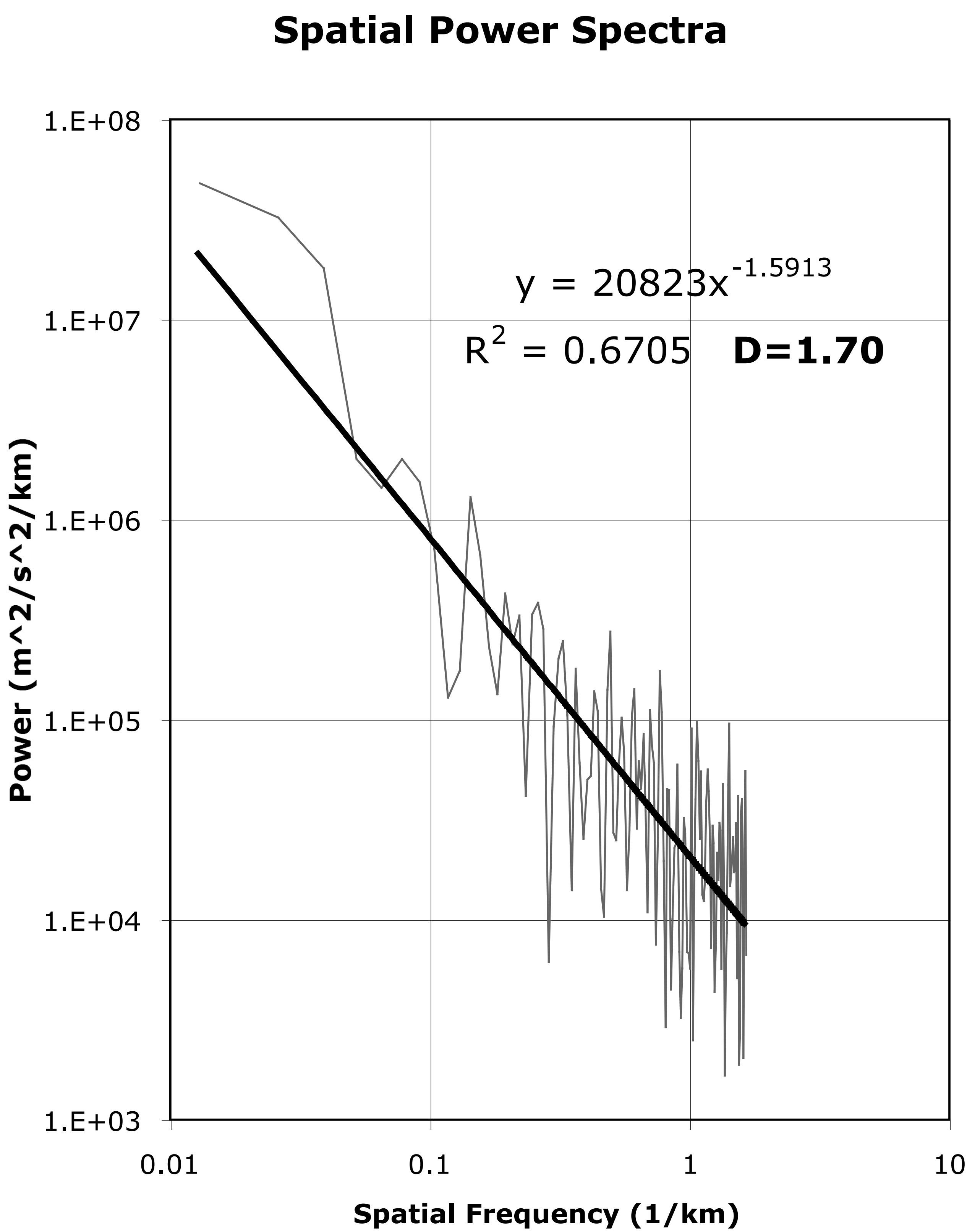

Geologic Unit vs. Shear Velocity
30 m Shear Wave Velocity (m/s)
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
10
11
12
Geologic Unit (see Table 2)
401.5 m/s ± 17.68
367.55 m/s ± 38.38
361.0 m/s ± 0
424.0 m/s ± 72.12
281.64 m/s ± 12.13
288.93 m/s ± 32.62
359.43 m/s ± 49.86
386.90 m/s ± 45.84
566.45 m/s ± 80.06
263.32 m/s ± 26.56
596.88 m/s ± 53.69

**Figure 4**



Soil Type vs. Shear Velocity
30-m Shear Wave Velocity (m/s)
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
7
8
9
Soil Unit (see Table 3)
244.5 m/s ± 10.61
246.2 m/s ± 14.67
453.0 m/s ± 100.99
392.0 m/s ± 127.55
266.4 m/s ± 21.74
411.0 m/s ± 0
580.8 m/s ± 47.84
280 m/s ± 37.65


**Figure 5**



Spatial Power Spectra
y = 20823x^-1.5913
R^2 = 0.6705   D=1.70
1.E+08
1.E+07
1.E+06
1.E+05
1.E+04
1.E+03
Power (m^2/s^2/km)
0.01
0.1
1
10
Spatial Frequency (1/km)


**Figure 6**

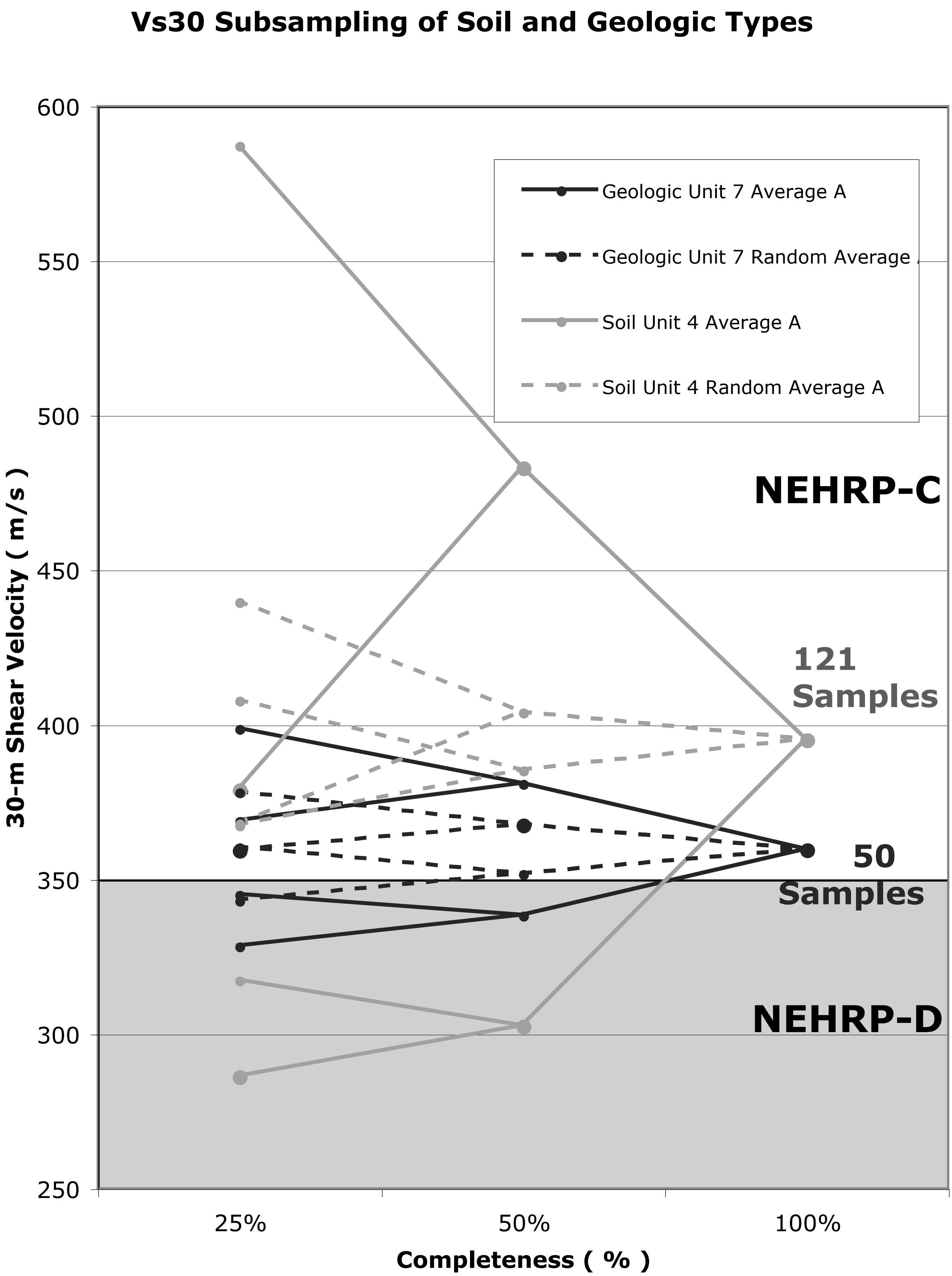
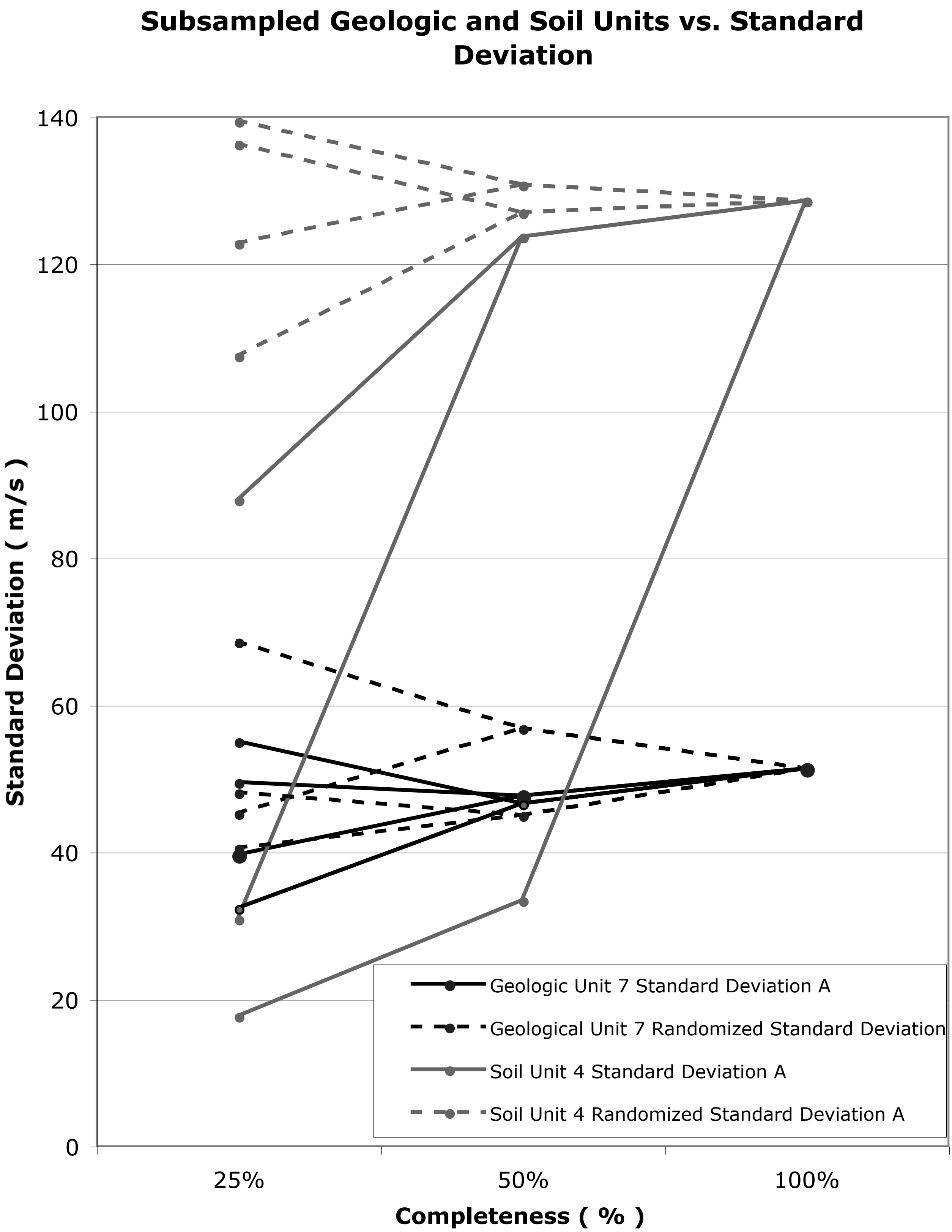
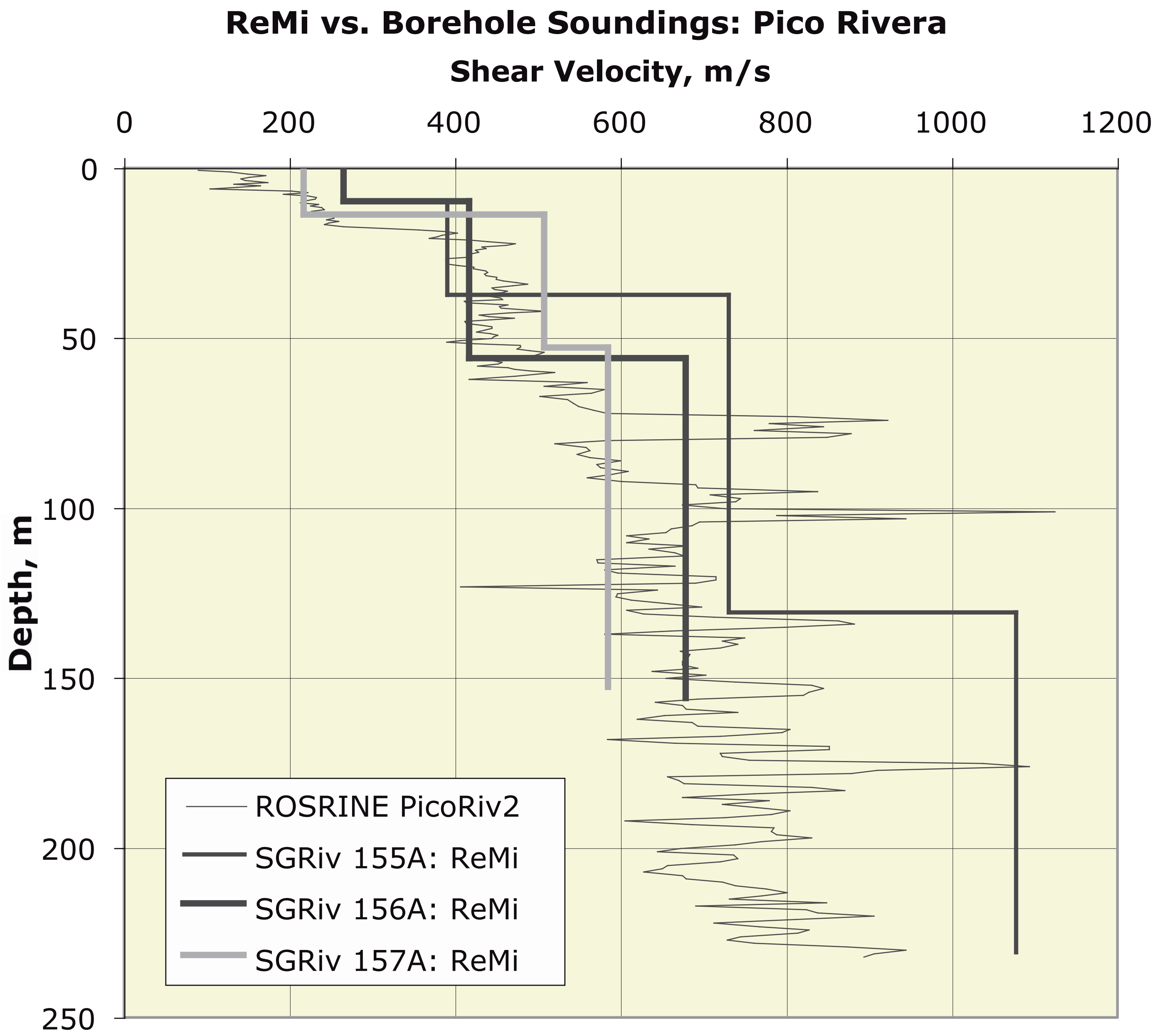

Vs30 Subsampling of Soil and Geologic Types
Geologic Unit 7 Average A
Geologic Unit 7 Random Average
Soil Unit 4 Average A
Soil Unit 4 Random Average A
NEHRP-C
121 Samples
50 Samples
NEHRP-D
30-m Shear Velocity ( m/s )
600
550
500
450
400
350
300
250
25%
50%
100%
Completeness ( % )

**Figure 7**



Subsampled Geologic and Soil Units vs. Standard Deviation
Standard Deviation ( m/s )
0
20
40
60
80
100
120
140
25%
50%
100%
Completeness ( % )
Geologic Unit 7 Standard Deviation A
Geological Unit 7 Randomized Standard Deviation
Soil Unit 4 Standard Deviation A
Soil Unit 4 Randomized Standard Deviation A


Figure 8



ReMi vs. Borehole Soundings: Pico Rivera
Shear Velocity, m/s
0
200
400
600
800
1000
1200
0
50
100
150
200
250
Depth, m
ROSRINE PicoRiv2
SGRiv 155A: ReMi
SGRiv 156A: ReMi
SGRiv 157A: ReMi


Figure 9